Harmonics Measurements with Radially Bucked Tangential Probes

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I. Introduction

This note discusses a class of magnetic field harmonics measurement probes which is designed around a radially bucked tangential (RBT) winding geometry. The advantages of this type of probe may include fast, and low-cost procurement of harmonics probes over a large range of radii (5mm – 150mm) (e.g. using printed-circuit board technology), a compact geometry (allowing possibility of new, high-speed, probe designs), and well-controlled (and easily measurable) conductor placement with potentially high analog bucking ratio.

II. RBT Description

A simplified sketch of a traditional tangential style probe is shown in Figure 1. The winding labeled "T" is the tangential winding, typically with angular opening of ~15deg.

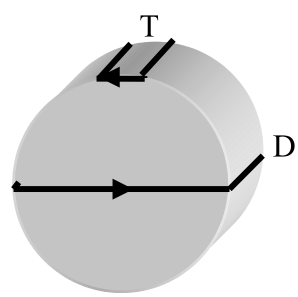

Fig. 1

A dipole bucking winding is shown in the figure, labeled as "D". Dipole buck windings are, in fact, usually a pair of windings, symmetrically offset in phase wrt "T" by an offset angle between them such that a linear combination of the two windings (nominally with coefficients of 1) will buck out the dipole field in "T" leaving it only sensitive to harmonics. An analog combination of these windings typically yields a bucking factor of 100-200. In order for this to be the case, the number of turns of the windings needs to also be accounted for in the design – typically a ratio of 15:1 for T:D; the large number of T turns also increases the sensitivity to the higher order harmonics. Present tangential probes at MTF also have two quadrupole bucking windings, likewise offset from the phase of the tangential, so that quadrupole field can be removed in the case of the quad being the fundamental field component.

A schematic of RBT design is shown in Fig. 2.

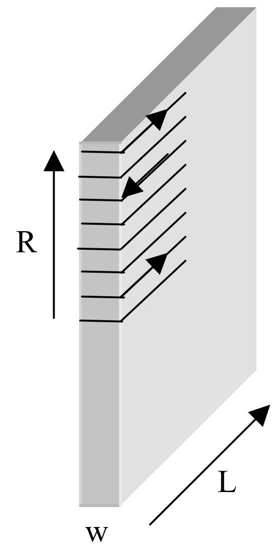

Fig. 2

Basically, windings are all parallel conductors around the width of a mechanically precise block. All windings are tangential with the number of turns being limited by the density of the conductors. Bucking is achieved by having some turns running in a direction opposite to that of others. This type of ‘radial bucking’ can remove quadrupole by having twice as many turns at half the radius of the outer turns, and can remove dipole by making the total number of turns in one direction equal to the number of turns of the opposite sense.

Mechanical mounting features in the PCB design could be added with precisely located holes wrt the windings such that a coupling could rotate the probe around the geometric center of its windings (see Fig. 3). These features could be of fixed size regardless of probe radius (for radius larger than coupling size) such that couplings could be standard.

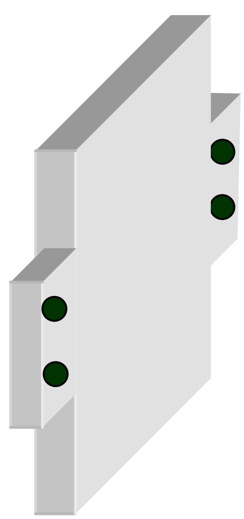

Fig. 3

The RBT could be supported within a rigid, rectangular or hemispherical fixture that would clamp around it and could help insure its straightness and stiffness (e.g. using ceramic, G10, etc.).

The easiest way to manufacture such a probe is using printed circuit board (PCB) technology. A more precise schematic of how this might be done is shown in Fig. 11 (attached at the back of this note) with the conductor connections shown in Figure 12 (note that the winding direction reverses after four turns and then again after another eight). PCB manufacturers are willing to select substrate with uniformity of thickness at the level of 1-2 mils and also claim conductor placement accuracy typically at this level. The cost would be about \$1-2k for a half dozen boards for standard conductor densities (this turns out to give spacing of about 1mm – though there might be room for a factor of 2 or so increase in this density with some added cost). The standard limitations on PCB manufacturing size are about 12"H x 24"L x 0.25"W (0.3m H x 0.5m L x 5mm W). Using PCB manufacturing would make it easy to obtain RBT probes for specific applications such as integer twist-pitch length or small aperture probes. Note that the typical PCB tolerances would be expected to give analog bucking ratio of about 100-200 for each loop for a 5mm width board. If variations on the PCB are random, the total bucking ratio should benefit from statistics, and would be a factor $\sqrt{N_{turns}}$ better. Though this level of analog bucking is all that is really needed in measurement applications to limit the effects of vibration, [1], the position of turns on the RBT could also be specified to give phase differences that could be used for digital bucking. This would effectively yield two each of 'dipole' and 'quad' buck windings for digital bucking with phase offset similar to traditional tangential probes.

Another option for probe design would be to start first with a block of uniformly thick material and have the parallel conductors attached to the surface in the form of ribbon cable (or via machined grooves in the surface). Ribbon cable conductor densities and parallelism can be very high. The RBT measurement probe could then be of arbitrary length, constrained only by the mechanics of the winding block and mechanical support. The PCB technique obviates the necessity of actually forming the wire loops while a machined or ribbon cable version would, in addition to the mechanical assembly work, require some tedious electrical connection. In the case of using machined grooves, a continuous wire could be used to wind many parallel turns to reduce splicing (as for conventional probe winding), or a Litz wire could be used. (These of course could be at discrete radii rather than uniformly spread over the block).

III. Sensitivity and Bucking Calculations

The flux measured during a rotating probe measurement can be written as

$$\Phi(\theta) = \Re\left(\sum_{n=1} K_n C_n e^{-in(\theta+\theta_0)}\right) \qquad (1)$$

where Cn are the harmonic coefficients and Kn are the sensitivities calculated as

$$K_n = \sum_{m\ wires} \frac{NLR_0}{n} \frac{(x_m + i\ y_m)^n}{R_0^n} \operatorname{sgn}(m) \qquad (2)$$

where *sgn(m)* gives the sign of the wire depending whether current flow is positive or negative and where the summation is over the position of every wire on the probe (or a point representing some average of wires). Even if the geometry is imperfect, knowing the position of each wire allows calculation of the correct Kn to accurately determine the field coefficients. For an RBT probe, the windings can be sorted into three parts: a ‘harmonics’ part (the turns at the largest radius all going in the same direction), a quadBuck part (the turns centered around half the radius to buck quadrupole) and a dipole buck part (the turns closest to the rotational center which are used to buck the dipole. A schematic of this is shown in Fig. 4.

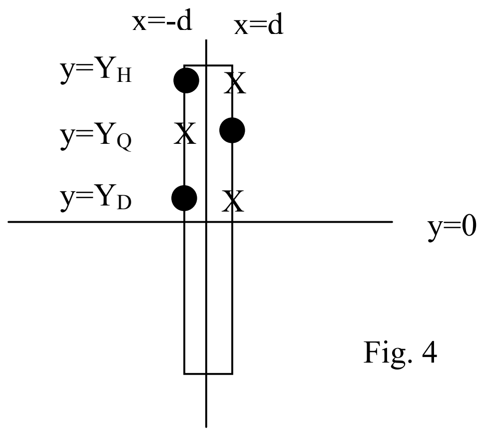

Fig. 4

Denoting the sensitivities for these three regions by superscript (H, Q, D), and the order sensitivity by a subscript (n=1, 2), we can then write the sensitivities to the dipole and quad fields at each of the three regions in Fig. 4 by

$$K_1^H = \left(N_H L\,(d + i\,Y_H)\right) - \left(N_H L\,(-d + i\,Y_H)\right) = N_H L 2d = N_H\ L\ w$$

$$K_1^Q = N_Q\ L\ w \qquad (3)$$

$$K_1^D = N_D\ L\ w$$

and

$$K_2^H = \frac{N_H L R_0}{2}\left(\frac{(d + iY_H)}{R_0}\right)^2 - \frac{N_H L R_0}{2}\left(\frac{(-d + iY_H)}{R_0}\right)^2 = iN_H L\ w \frac{Y_H}{R_0}$$

$$K_2^Q = iN_Q L\ w \frac{Y_Q}{R_0} \qquad (4)$$

$$K_2^D = iN_D L\, w \frac{Y_D}{R_0}$$

The condition of bucking the dipole is met when

$$\sum K_1 = 0 \quad \rightarrow \quad N_H - N_Q + N_D = 0$$

and for quad bucking by

$$\sum K_2 = 0 \quad \rightarrow \quad N_H Y_H - N_Q Y_Q + N_D Y_D = 0$$

The conditions for bucking both dipole and quadrupole are satisfied, by now requiring

$$Y_Q = \frac{Y_H + Y_D}{2} \tag{5}$$

and

$$N_H = N_D = \frac{N_Q}{2} \tag{6}$$

.

Note that these conditions are met using only the part of the RBT starting at the center of rotation and going to the max. radius, R; a second RBT probe could then be made on the remaining half (for example, a “dipole buck” RBT winding on the upper half and “dipole + quad buck” on the lower). One can also try to have the lower half take some duty of dipole bucking and thereby try to boost the number of harmonics winding turns.

As design examples, PCB versions of RBT probes are compared to a standard 15 turn tangential style probe of same length and radius. The parameters for these probes are listed in Table 1. PCB conductor spacing of 1mm and 0.5mm are considered.

	PCB half	turn positions	polarity
Dip+QuadBuck L=0.5m, R=20mm	upper	16-20 mm	+
	upper	6-15 mm	--
	upper	1-5 mm	+
DipoleBuck L=0.5m, R=20mm	lower	11-20 mm	+
	lower	1-10mm	--

Table 1

Fig. 5 shows the harmonic sensitivities of the RBT probes relative to the tangential coil. Overall, the sensitivity for the quad + dipole bucked RBT probe is about a factor of 5-10 lower than the tangential coil for 1mm spacing and factor 3-5 lower for the 0.5mm spacing. The dipole buck RBT probe mostly shows about a factor 3-5 lower sensitivity (except n=10) for 1mm conductor spacing, and only a factor of 2 lower sensitivity when the conductor density is increased to 0.5mm.

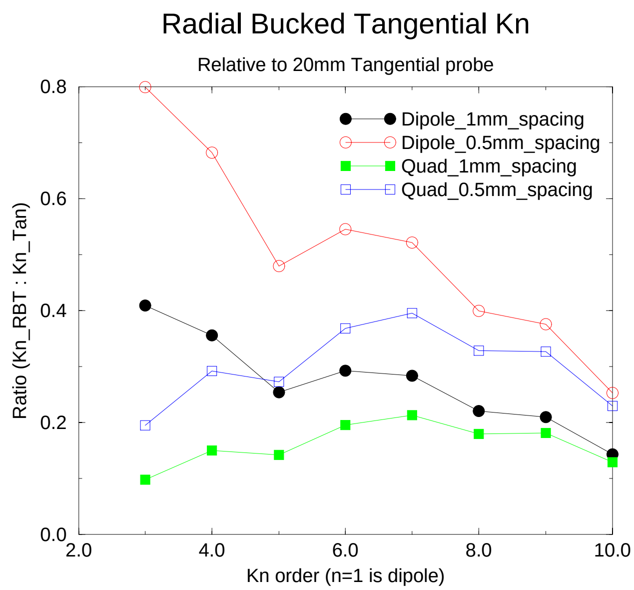

Fig. 5

Since the sensitivity of the PCB version of the RBT is lower compared to standard tangential style probes, signal size in specific applications has to be considered. However, since the bucking ratio for PCB RBT probes is expected to be generally higher, this should at least partially offset the lower sensitivity and may leave harmonics signal to noise comparable. If boosting sensitivity of the RBT is necessary, high conductor density Litz or ribbon cable probably needs to be employed.

IV. Error Analysis

A full error analysis will not be shown here, but effects of vibrations, off-axis rotation, etc. should be similar to the effects seen in standard tangential probes. Some more RBT-specific construction errors might be a) a wedge-shaped board width, b) systematic shift in the conductors on one side relative to the position of the conductors on the other side, c) slant of the board (either bow or support structure is bowed). These are shown schematically in Fig 6. Though conductor placement and board flatness should be able to be controlled during PCB manufacturing at the level of 1-2 mils (25-50um), the magnitude of the sensitivity errors in this analysis were simulated using construction errors of δ=0.25mm .

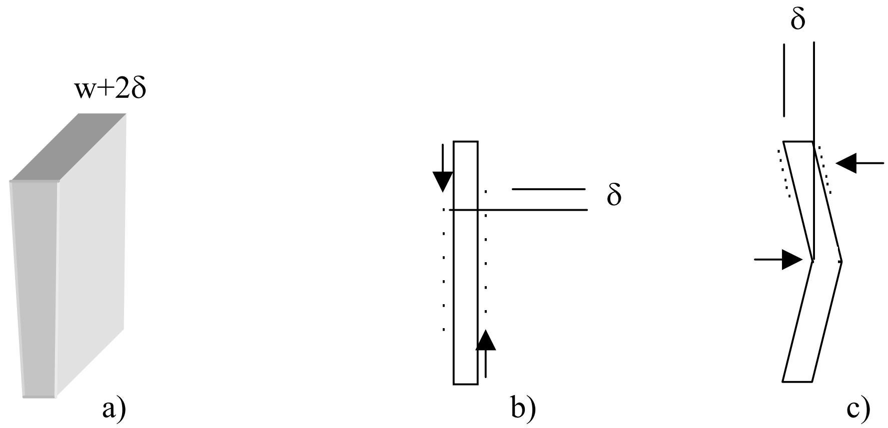

Fig. 6

The graph in Fig 7 shows the change in real and imaginary parts of the sensitivity normalized to the sensitivity amplitude for the cases of the three errors shown above applied to a dipole buck RBT probe. These are shown for non-fundamental harmonics (n>2). Note that the fractional Kn shown is a measure for both the amplitude change and phase change (i.e. it also relates the amount of a particular harmonic amplitude that would appear to change from normal to skew (or vice versa) as a result of phase error). In all cases the harmonics would be distorted by less than 15%. Moreover, these effects could be largely eliminated by measuring the conductor locations and using these to compute the actual sensitivities. Inspecting a PCB would be easy to do; additional calibrations could be performed in a reference magnet if needed. The only error of the three which affected bucking ratio was the wedge error, which created a sizable difference in the size of the larger radius turns compared to the bucking turns at smaller radius. The bucking ratio was 20 for the 2δ=0.5mm error used.

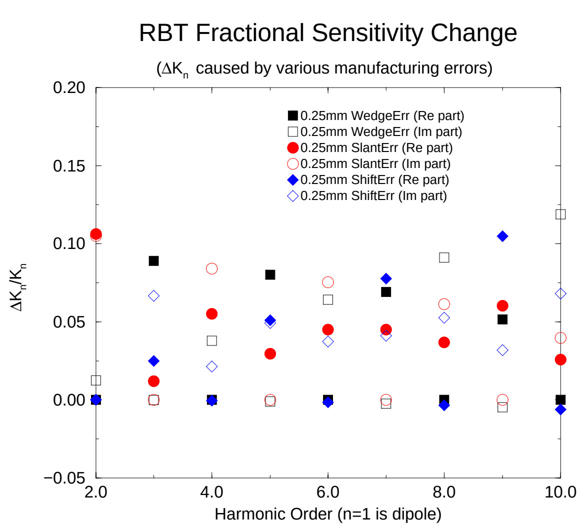

Fig. 7

The errors are a bit larger in the case of the dipole + quad buck RBT probe, as shown in Figure 8. The bucking ratio for the quadrupole (fundamental) was reduced to 40, and again occurred only in the case of the wedge error.

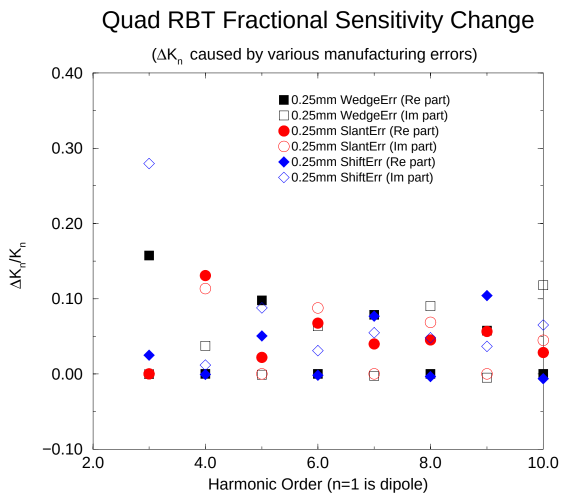

Fig. 8

V. High speed probes based on RBT

High speed measurements of harmonic fields are needed when the ramp rate is very fast (as for fast-cycling booster magnets which ramp at ~30KA/s) or when the harmonics change relatively rapidly at low (or zero) ramp rates (e.g. during snap-back after the accelerator cycle injection porch).

Since a RBT probe gives a bucked measurement of field harmonics over a small width, an ensemble of such probes could be assembled (shown schematically in Fig 9) which, sampled simultaneously with fast multi-channel ADC's, could yield snapshots of magnetic field at very high sampling rates. (Given expected bucking ratios, the ADC resolution should not be a limitation).

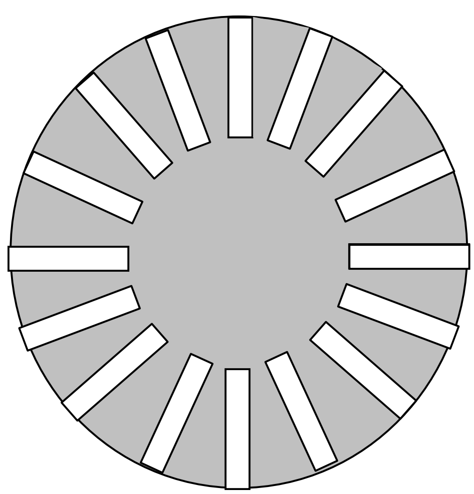

Fig. 9

For high ramp-rate measurements, the RBT ensemble would remain stationary with the flux change being generated by the changing field. Sampling could be arbitrarily fast – limited only by hardware and signal size considerations. As an example, for an ensemble of 0.5m long, 5mm wide RBT probes, and magnet current ramp-rate of 30kA/s (corresponding to 21 T/s), the flux of 1 unit of harmonics measured at the reference radius is ~3e-08 Vs per msec (i.e. sampled at 1kHz). This should be measurable with a good integrator or ADC.

For fast measurements at low ramp-rates, measurements can be made while the RBT probe ensemble is rotated. Each angular change would generate a flux change at each RBT vertex. The vertices, taken sample-by-sample as an ensemble, would form a snapshot of flux from which the harmonics could be determined. If, for example, the probe is rotated at 2Hz with 128 angular triggers for each rotation, then the sampling of the field harmonics would effectively occur at 256Hz. A simulated rotation of data is shown in Figure 10.

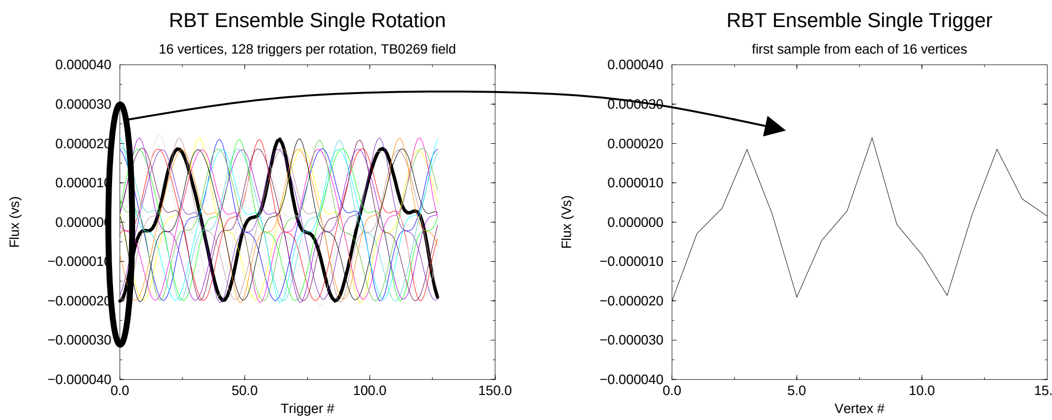

Fig. 10

Sensitivity

Assuming that about half the radius needs to be a ‘core’ around which the ensemble is assembled, the number of turns of the harmonics and bucking windings would be lower by a factor 2 (with the maximum radius of the windings remaining the same). The sensitivity (and therefore the signal size) for a RBT ensemble would be a factor 4 or 3 lower than a single rotating RBT probe for n=2, n=3 respectively, but increasingly the same for higher orders.

Mechanically, the ensemble support would have to be designed to allow as large a height of the individual RBT probes as possible to maximize the sensitivity, while trying to keep the ensemble as rigid and geometrically accurate as possible. This could be done by machining of a solid cylinder, or perhaps by an aggregate of stamped thin G10 or molded ceramic laminations

Harmonics Analysis

To perform analysis of the ensemble snapshot, the delta flux should be used directly. The change in flux for a given vertex of a RBT ensemble being rotated is given by

$$\begin{aligned}\Delta\Phi(\theta) &= \Re\left(\sum_{n=1} K_n C_n \left(e^{-in(\theta_2+\theta_0)} - e^{-in(\theta_1+\theta_0)}\right)\right) \\ &= \Re\left(\sum_{n=1} K_n C_n \left(2i\sin\frac{n\Delta\theta}{2}\right) e^{-in(\theta+\theta_0)}\right)\end{aligned} \tag{7}$$

where θ is $(\theta 1+\theta 2)/2$ and $\Delta\theta=\theta_2-\theta_1$ is the change in angle between triggers (not the angular separation of the vertices). If the factor of

$$\left(2i\sin\frac{n\Delta\theta}{2}\right) \tag{8}$$

is then absorbed into the sensitivity factor, K_n, the result is identical in form to equation (1) and can be used to determine the harmonic coefficients directly from the delta flux data of the ensemble.

Errors

To the extent that the bucking ratios (expected to be 100-1000) at each RBT vertex are not uniform, there can be large false harmonics generated by the presence of residual un-bucked fundamental field. However, amplitude and distribution of the bucking variability should remain stable to a high degree. If this is indeed the case, the false harmonics, though large, should be able to be removed using calibration to harmonics measured in stable (DC) fields.

The false harmonics can be measured in several ways. In the case of using the RBT ensemble in “AC mode” (i.e. stationary with high current ramp-rate), this can be accomplished by comparing the harmonics which are obtained through flux change during a ramp from zero to some DC current level, to the DC harmonics measured with a rotating coil at that current. During “DC mode” (i.e. rotation) of the RBT ensemble, the harmonics of any one of the vertices taken during a full rotation in stable field can be compared with each ensemble ‘snapshot’ obtained during the same rotation. Another DC measurement of the false harmonics could be obtained by sample-by sample combination of the residual fundamental field found in the bucked data of each vertex obtained during a full rotation in a stable magnetic field. The combination of these residuals should yield the false harmonic pattern caused by the bucking variation among vertices. Note that the false harmonics from un-bucked fundamental fields are minimized by having good uniformity in bucking ratios among vertices.

A second contribution to false harmonics (though at a much lower level) would arise from imperfect assembly of the mechanical geometry of the ensemble. The effect of ensemble imperfections during the field snapshot would be equivalent to a (repeatable) vibration pattern – i.e. at different angles, the position of the tangential winding would appear displaced from its ideal position by some amount. However, because of the bucking present at each vertex, any 'feed-up' effects from the fundamental field are greatly reduced [1], and the effect of 'vibration' would have little impact on the measured field unless mechanical errors are significant (tolerances may be at the level of few mils (0.1 – 0.2mm)). The magnitude of these errors can be inspected by comparing sample-by-sample combination of the data from the vertices taken during a full rotation in stable field (with fundamental field residuals suppressed this time) to the DC values obtained by a single vertex rotation. Note that these errors are minimized by having good mechanical assembly geometry and high average bucking ratio. In any case, these again would be stable effects, and could be removed by calibration (if necessary).

VI Conclusion

Magnet measurement probes designed around radially bucked tangential geometry should be able to provide accuracies comparable to present tangential probes and should be able to be made quickly and cheaply using printed circuit board technology. The sensitivity to harmonics of PCB versions will be lower by a factor of ~5 than similarly dimensioned standard tangential probes, but this may not be a problem for most applications and may be at least partially compensated for by a better bucking ratio. This may prove to be a useful tool in standard probe design applications as well for special purpose probes (e.g. for integer twist-pitch probes or probes which are optimally sized for particular applications). In addition, the compact geometry allows new types of probes to be built that could measure harmonic fields at very high speeds both during AC and DC measurements. These high speed probes might be useful for measuring magnets for the proposed Proton Driver at FNAL as well as for understanding magnet issues related to Tevatron RunII.

To further explore the feasibility of this type of probe, some sort of prototype could be fabricated and measurements compared to results from existing probes. A small array of probes could also test the concepts of the high-speed RBT ensemble in measuring the fundamental field of a dipole magnet.

[1] J. DiMarco et al., "Influence of Mechanical Vibrations on the Field Quality Measurements of LHC Interaction Region Quadrupole Magnets", IEEE Trans. on Applied Superconductivity, Vol. 10, No. 1, March 2000.

Fig. 11

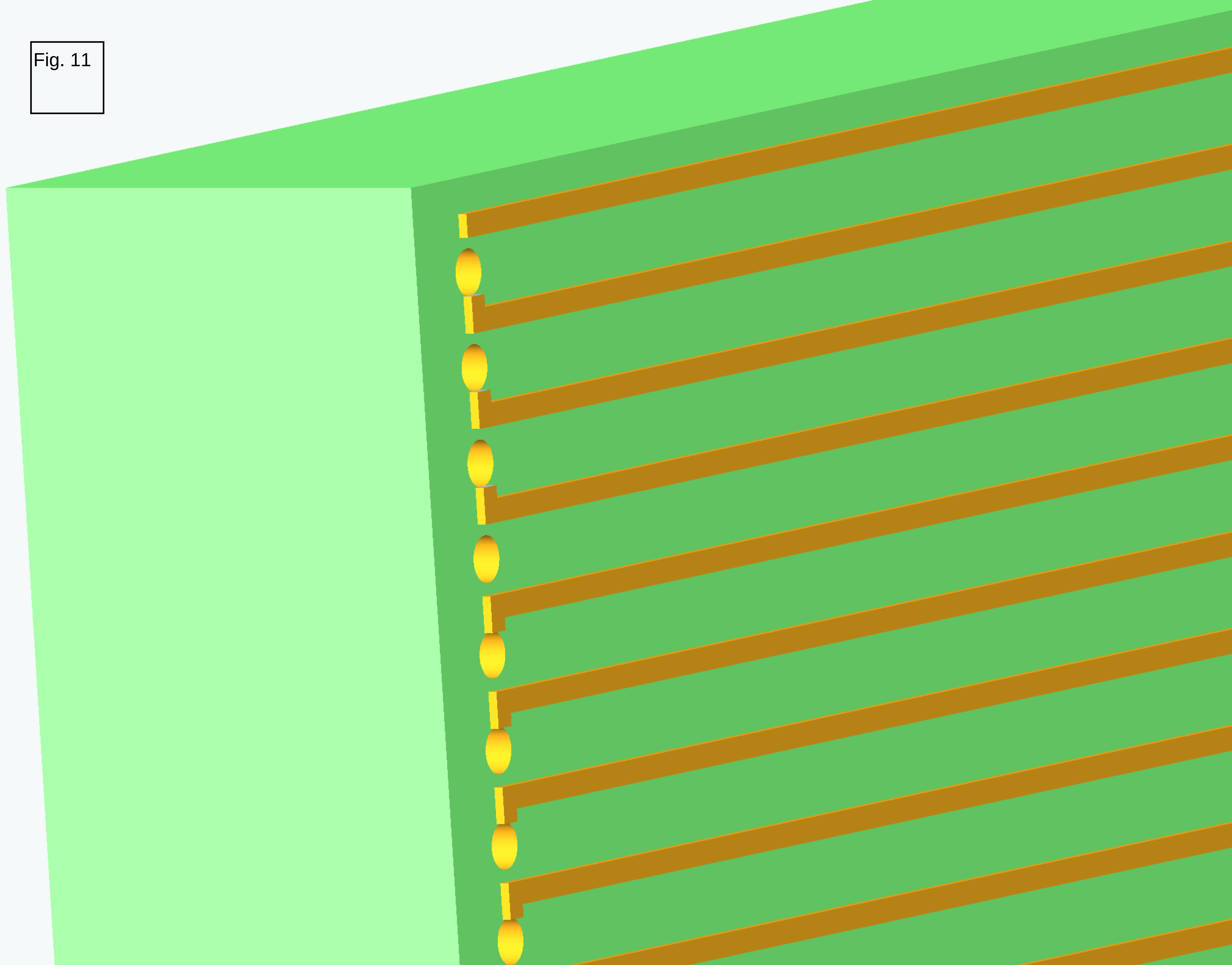

Fig. 12